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7 Measurement of the ratio of differential cross sections for  
8 W and Z boson production as a function of transverse momentum  
9 in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV  
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## Abstract

We report on a measurement of the ratio of the differential cross sections for  $W$  and  $Z$  boson production as a function of transverse momentum in proton–antiproton collisions at  $\sqrt{s} = 1.8$  TeV. This measurement uses data recorded by the DØ detector at the Fermilab Tevatron in 1994–1995. It represents the first investigation of a proposal that ratios between  $W$  and  $Z$  observables can be calculated reliably using perturbative QCD, even when the individual observables are not. Using the ratio of differential cross sections reduces both experimental and theoretical uncertainties, and can therefore provide smaller overall uncertainties in the measured mass and width of the  $W$  boson than current methods used at hadron colliders. © 2001 Published by Elsevier Science B.V.

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## 1. Introduction

The DØ Collaboration has recently published [1,2] measurements of differential cross sections for  $W$  and  $Z$  boson production as a function of transverse momentum ( $p_T$ ). Both measurements are in good agreement with combined resummed and perturbative QCD models, such as those in Refs. [3–5]. For the analyses of data taken during 1992–1996 (Fermilab Tevatron Run 1), we have used the resummed calculation of Ref. [4] fitted to our observed  $Z \rightarrow e^+e^-$  differential cross section to extract the non-perturbative phenomenological parameters of the theory. The resummed calculation was then used to predict  $W$  boson observables such as the electron and neutrino transverse mo-

menta and as input to a Monte Carlo model of  $W$  boson production and decay, which we used to extract the mass [6] and production cross section [7] of the  $W$  boson.

Ref. [8] proposes an alternative method of predicting  $W$  boson observables from measured  $Z$  boson quantities. This is based on the theoretical ratio of the  $W$  to  $Z$  boson differential cross sections with respect to variables that have been scaled by their corresponding vector boson masses. Because production properties of  $W$  and  $Z$  bosons are very similar, the large radiative corrections that affect the individual distributions cancel in the ratio. The ratio can therefore be calculated reliably using perturbative QCD (pQCD), with no need for resummation, even at small values of the transverse momenta of the vector bosons, for which the radiative corrections factorize from the hard process and therefore cancel in the ratio. The theoretical uncertainties stemming from the perturbative

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1 expansion are consequently well-understood, and are  
2 smallest at very low  $p_T$ .

3 The basic proposal of Ref. [8] is to use pQCD  
4 calculations and the measured  $Z$  boson observables  
5 to extract the  $W$  boson observables. Compared to  
6 the standard method used previously to extract  $W$   
7 boson observables, the present method reduces both  
8 theoretical and experimental systematic uncertainties.  
9 However, it introduces a statistical contribution to the  
10 uncertainty from the number of events in the  $Z$  boson  
11 candidate sample. Such a trade-off will eventually  
12 result in smaller overall uncertainties, especially when  
13 used with the high statistics samples expected from  
14 Run 2 of the Tevatron.

15 Corroborating the agreement of the pQCD calculation  
16 with data is vital if the new procedure is to be used  
17 to improve the measurement of the  $W$  boson mass  
18 in future collider runs. In this Letter, we will check  
19 the validity of the method using the measured differential  
20 cross sections for  $W$  and  $Z$  boson production  
21 as a function of transverse momentum. Both distributions  
22 were measured at the Tevatron [1,2,9], where  
23 the systematic uncertainty on the  $p_T^W$  at lowest trans-  
24 verse momentum is four times larger than the corre-  
25 sponding uncertainty in  $p_T^Z$ . The uncertainty in  $p_T^Z$  is  
26 dominated by statistics. Hence, once large samples of  
27  $Z$  boson events become available, it is expected that,  
28 if theoretical uncertainties can be kept small, using  
29 the pQCD prediction and the well-measured  $p_T^Z$  dis-  
30 tribution to predict the  $p_T^W$  distribution should lead  
31 to smaller overall uncertainties on the measured mass  
32 and width of the  $W$  boson, relative to current methods  
33 used at hadron colliders.

34 The main difference between the production prop-  
35 erties of the  $W$  and the  $Z$  bosons arises from the dif-  
36 ference in their masses. We will therefore introduce  
37 variables that are scaled by the corresponding vector  
38 boson mass  $M_V$ . The ratio of differential cross sec-  
39 tions for the scaled  $W$  and  $Z$  boson transverse mo-  
40 ments ( $p_T^W/M_W$  and  $p_T^Z/M_Z$ ) is defined as

$$42 R_{pT} = \left[ \frac{d\sigma^W}{d(p_T^W/M_W)} \right] / \left[ \frac{d\sigma^Z}{d(p_T^Z/M_Z)} \right], \quad (1)$$

43 where  $d\sigma^V/dp_T^V$  is the standard differential cross  
44 section for vector boson production  $\sigma(p\bar{p} \rightarrow V + X)$   
45 as a function of transverse momentum  $p_T^V$ . Eq. (1)  
46 can be used to predict the differential cross section

47 for  $W$  bosons with respect to the non-scaled transverse  
48 momentum [8]:

$$\frac{d\sigma^W}{dp_T^W} \Big|_{\text{predicted}} = \frac{M_Z}{M_W} \times R_{pT} \times \frac{d\sigma^Z}{dp_T^Z} \Big|_{\text{measured}}^{p_T^Z = \frac{M_Z}{M_W} p_T^W}, \quad (2)$$

49 where  $R_{pT}$  is calculated using pQCD. In this Letter,  
50 we present the first measurement of  $R_{pT}$ , and compare  
51 it to the calculation of Ref. [8]. For completeness, we  
52 repeat the exercise presented in Ref. [8] and use our  
53 measured differential  $Z$  boson cross section in Eq. (2),  
54 and  $R_{pT}$  from Ref. [8], to obtain the differential  $W$   
55 boson cross section and compare it to our published  
56 result [1].

## 2. Data selection

63 We keep modifications to the published DØ analy-  
64 ses [1,2] to a minimum, but, at the same time, we try  
65 to cancel as many experimental uncertainties as pos-  
66 sible in measuring  $R_{pT}$ . The uncertainty in the inte-  
67 grated luminosity of the data samples (4.3%) is the  
68 dominant uncertainty in the individual cross sections.  
69 It cancels completely when taking the ratio, as long as  
70 the same data sets are used to select the final  $W$  and  $Z$   
71 boson candidate samples. In this analysis, we keep the  
72 event selections and corrections for background, effi-  
73 ciency, acceptance, and detector resolutions identical  
74 to those in the published results [1,2], but require total  
75 overlap in the data-taking runs for the  $W$  and  $Z$  bo-  
76 son event samples. In addition, we exclude events at  
77 collision times with large beam losses from the Main  
78 Ring accelerator [7]. These beam losses can create sig-  
79 nificant energy deposits in the calorimeter that pro-  
80 duce events with large false transverse momentum im-  
81 balance that could pass our  $W$  boson selection crite-  
82 ria. Due to these additional requirements, the  $Z$  bo-  
83 son sample was reduced from 6407 to 4881 events.  
84 About half of the events were lost due to tightening of  
85 beam quality conditions, and half because the  $W$  trig-  
86 ger was not available or was prescaled. The  $W$  sample  
87 was reduced from 50488 to 50264 events when we re-  
88 moved runs for which the  $W$  trigger was prescaled.  
89 The final integrated luminosity for both samples is  
90  $(84.5 \pm 3.6) \text{ pb}^{-1}$ .

91 We have investigated whether additional sources  
92 of error could be cancelled in the ratio. There are

1 four sources of systematic error that contribute to  
 2 the  $W$  and  $Z$  boson cross sections. These arise from  
 3 uncertainties in the background estimate, the event  
 4 selection efficiency, and the unfolding procedure used  
 5 to correct for acceptance and detector resolution.

6 The dominant sources of background in both the  
 7  $W$  and the  $Z$  boson analyses are from multijet and  
 8 photon-jet events, where the jets pass our electron  
 9 identification criteria. In the case of the  $W$ , a large  
 10 imbalance in the transverse energy has to arise to  
 11 mimic the presence of a neutrino. The way multijet  
 12 or photon-jet events mimic  $W$  or  $Z$  boson events  
 13 is quite different, and the methods used to estimate  
 14 background are independent. We therefore cannot  
 15 cancel any contribution to the error in the ratio arising  
 16 from background estimates.

17 Acceptance and unfolding corrections are applied  
 18 using a parameterized Monte Carlo [6]. The main  
 19 contribution to the error is from the modeling of the  
 20 detector. For the  $W$  analysis, we rely completely on the  
 21 measurement of the energy of the recoiling hadrons,  
 22 whereas for the  $Z$  boson measurement we use the  
 23 electromagnetic energy deposited by the electrons. We  
 24 therefore do not benefit from cancellation of errors in  
 25 the acceptance/unfolding procedure.

26 The uncertainty in the efficiency has contributions  
 27 from the trigger and offline electron identification.  
 28 The level 0 trigger, which requires the detection of an  
 29 inelastic collision via simultaneous hits in the forward  
 30 and backward level 0 scintillation detectors [10], is  
 31 common for  $W$  and  $Z$  boson events. The uncertainty  
 32 in this trigger therefore cancels completely in the ratio.  
 33 However, its contribution to the error in the efficiency  
 34 is negligible (0.5% out of a total of 3.5%).

35 Although the triggers and the offline electron iden-  
 36 tification criteria used in the  $W$  and  $Z$  boson analyses  
 37 are different, the main contribution (3%) to the error  
 38 in the efficiency comes from a common source, the so-  
 39 called  $u_{||}$  efficiency [6]. This inefficiency arises when  
 40 the energy flow close to the electron increases as re-  
 41 coiling hadrons approach the electron. It is therefore  
 42 a topological effect produced by the proximity of the  
 43 electron to the jet, and has the largest effect at a bo-  
 44 son transverse momentum of about 20 GeV [2]. The  
 45  $u_{||}$  efficiency is calculated on an electron-by-electron  
 46 basis using the parameterized Monte Carlo. The error  
 47 in the  $u_{||}$  efficiency is estimated from  $W$  and  $Z$  bo-  
 48 son events, generated in HERWIG [12], and overlaid

49 with data taken from randomly selected  $p\bar{p}$  collisions.  
 50 Because this inefficiency depends on the proximity of  
 51 electrons to jets, it is difficult to estimate how much  
 52 of the uncertainty in the  $u_{||}$  efficiency cancels in the  
 53 ratio. To determine if further investigation of any pos-  
 54 sible cancellation of the uncertainty in  $u_{||}$  efficiency  
 55 was warranted, we estimated the effect on  $R_{pt}$  of a  
 56 complete cancellation of the contribution from the un-  
 57 certainty in  $u_{||}$  efficiency. This produced a maximum  
 58 reduction of uncertainty in  $R_{pt}$  of less than 5%. We  
 59 therefore concluded that no cancellations beyond the  
 60 uncertainty in the luminosity would improve signifi-  
 61 cantly the measurement of  $R_{pt}$ .

### 3. Scaled $W$ and $Z$ boson cross sections

**Eq. (1)** can be written

$$R_{pt}^{\text{th}} = \left( \frac{d\sigma^W}{dp_T^W} \right) / \left( \frac{d\sigma^Z}{dp_T^Z \times M_W/M_Z} \right),$$

where we use the mass ratio from the review of particle physics [11]

$$\frac{M_W}{M_Z} = 0.8820 \pm 0.0005.$$

In order to measure the scaled distributions without changing the  $p_T$ -binning of both the  $W$  and  $Z$  boson analyses, we keep the  $W$  bin boundaries ( $\delta_i$ ) identical to the ones in our published work, but because we require the same bin widths in the scaled variables  $p_T^W/M_W$  and  $p_T^Z/M_Z$ , we set the bin boundaries in the differential  $Z$  boson cross section to  $\delta_i/0.8820$ , and recompute the differential  $Z$  boson cross section accordingly.

**Table 1** shows the modified results for the  $W$  and  $Z$  boson cross sections, with the statistical and systematic contributions to the uncertainties shown separately. It is clear that the error in the ratio is dominated by the systematic uncertainty in the  $W$  cross section.

### 4. Measurement of $R_{pt}$

Based on the measured  $W$  and  $Z$  boson differential cross sections listed in **Table 1**, we extract the ratio of

1 Table 1

2 Summary of the measured  $W$  and  $Z$  boson differential production cross sections as a function of transverse momentum used to calculate the  
3 ratio. The error in the ratio is dominated by the systematic error in the  $W$  cross section

$p_T$ bin	$\frac{d\sigma(W \rightarrow ev)}{dp_T^W}$	Stat. error	Syst. error	$\frac{d\sigma(Z \rightarrow e^+e^-)}{dp_T^Z}$	Stat. error	Syst. error	
(GeV)	(pb/GeV)	(pb/GeV)	(pb/GeV)	(pb/GeV)	(pb/GeV)	(pb/GeV)	
0–2	109.48	4.61	12.35	11.94	0.53	0.35	49
2–4	206.21	6.85	24.64	19.63	0.65	0.57	50
4–6	171.32	5.65	9.29	14.34	0.53	0.44	51
6–8	133.60	4.65	9.46	11.19	0.48	0.36	52
8–10	103.48	4.04	6.95	8.05	0.41	0.27	53
10–12	77.46	3.46	7.25	6.18	0.37	0.21	54
12–14	63.58	3.20	4.16	4.74	0.33	0.15	55
14–16	47.77	2.77	4.29	3.39	0.28	0.11	56
16–18	37.67	2.42	2.73	3.27	0.28	0.17	57
18–20	30.50	2.20	1.74	1.94	0.22	0.11	58
20–25	22.02	1.23	1.22	1.59	0.12	0.08	59
25–30	13.94	0.93	1.07	0.946	0.097	0.051	60
30–35	9.51	0.73	0.84	0.848	0.092	0.043	61
35–40	6.79	0.63	0.51	0.435	0.066	0.022	62
40–50	3.96	0.37	0.31	0.325	0.040	0.016	63
50–60	1.82	0.25	0.25	0.180	0.029	0.009	64
60–70	1.14	0.20	0.23	0.0848	0.0197	0.0045	65
70–80	0.749	0.178	0.170	0.0385	0.0129	0.0020	66
80–100	0.310	0.059	0.088	0.0141	0.0054	0.0008	67
100–120	0.0822	0.0287	0.0255	0.00764	0.00383	0.00032	68
120–160	0.0433	0.0119	0.0118	0.00358	0.00180	0.00018	69
160–200	0.00769	0.00545	0.00482	0.00163	0.00111	0.00010	70

34 scaled cross sections as a function of  $p_T$ :

35
$$R_{pT}^{\text{exp}} = \left[ \left( \frac{d\sigma^W}{dp_T^W} \right) / \left( \frac{d\sigma^Z}{dp_T^Z} \right) \right] \times \frac{M_W}{M_Z} \\ 36 \times \frac{B(Z \rightarrow ee)}{B(W \rightarrow ev)}.$$

37 It should be recognized that the prediction for  $R_{pT}$  [8]  
38 was calculated for the ratio of the scaled  $W$  and  $Z$   
39 boson differential cross sections  $d\sigma^V/dp_T^V$ , but we  
40 measure the differential cross sections multiplied by  
41 their branching fractions to electrons  $(d\sigma^V/dp_T^V) \times$   
42  $B(V \rightarrow e)$ . We therefore must multiply our measure-84 ment by the ratio of the  $Z$  to  $W$  boson branching  
85 fractions. Because the measurement of the  $W$  boson  
86 branching fraction from the Tevatron is obtained pre-  
87 cisely from the ratio of  $W$  to  $Z$  production cross sec-  
88 tions [7], we use the result from the LEP Electroweak  
89 Working Group [13] for the  $W$  branching fraction,  
90 to avoid a circularity problem. We take the value for  
91 the  $Z$  branching fraction from the review of particle  
92 physics [11].

93
$$B(W \rightarrow ev) = 0.1073 \pm 0.0025,$$

94
$$B(Z \rightarrow ee) = 0.033632 \pm 0.000059.$$

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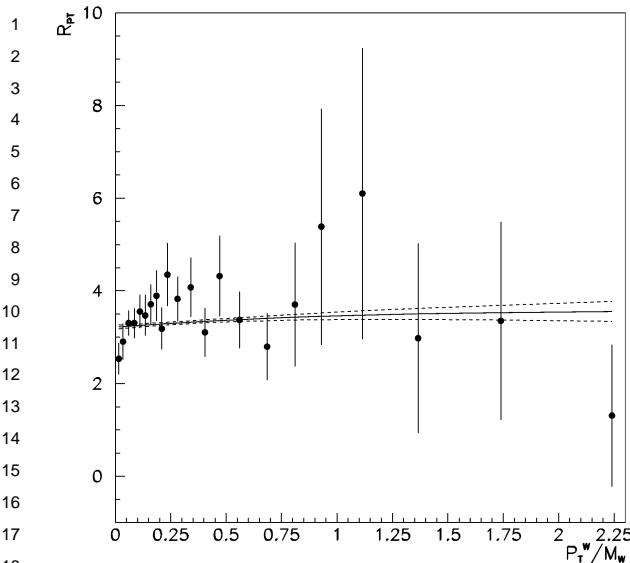


Fig. 1. Ratio of scaled differential cross sections  $R_{pT}$  for  $W$  and  $Z$  production. The solid line is the order  $\alpha_S^2$  theoretical prediction of Ref. [8], and the dotted lines are the one standard deviation uncertainties due to Monte Carlo integration. The error in the luminosity cancels completely in the ratio of the measured cross sections.

The result is shown in Fig. 1, and summarized in Table 2. The data are plotted at the value of  $p_T$  for which the theoretical prediction for  $R_{pT}$  is equal to its average in the bin, following the prescription of Ref. [14]. We observe that the measured  $R_{pT}$  agrees with the pQCD prediction [8]: the  $\chi^2$  for the comparison between data and theory is 18.3 for 21 degrees of freedom (63% probability). If we only consider the results in the first 12 bins, the  $\chi^2$  is 12.8 for 11 degrees of freedom, which corresponds to a probability of 31%.

We should mention that, at this time, the only uncertainty included in the theoretical prediction is the one arising from Monte Carlo integration. Additional uncertainties must be considered to determine whether the agreement between data and theory can be improved, in particular, if  $R_{pT}$  should be calculated to higher orders, or whether non-perturbative effects are playing a role at lowest  $p_T$ . Once the theoretical uncertainties are improved, this would provide the means for estimating the integrated luminosity at which the ratio method will provide a superior measurement of the  $W$  boson mass.

Table 2

Measured  $R_{pT}$ . The uncertainty in the luminosity for the  $W$  and  $Z$  samples cancels completely when taking the ratio

$p_T$ bin (GeV)	$p_T$ (GeV)	$R_{pT}$	Total error	
0–2	1.21	2.538	0.339	49
2–4	2.81	2.908	0.388	50
4–6	4.83	3.306	0.275	51
6–8	6.84	3.305	0.324	52
8–10	8.85	3.557	0.361	53
10–12	10.86	3.471	0.439	54
12–14	12.87	3.714	0.426	55
14–16	14.88	3.895	0.549	56
16–18	16.89	3.187	0.449	57
18–20	18.90	4.351	0.681	58
20–25	22.52	3.829	0.478	59
25–30	27.34	4.078	0.638	60
30–35	32.57	3.104	0.528	61
35–40	37.89	4.320	0.871	62
40–50	45.03	3.373	0.613	63
50–60	55.09	2.796	0.724	64
60–70	65.14	3.707	1.334	65
70–80	74.79	5.384	2.551	66
80–100	89.67	6.100	3.141	67
100–120	109.77	2.976	2.047	68
120–160	139.93	3.352	2.138	69
160–200	180.14	1.309	1.529	70

## 5. Extraction of $d\sigma^W/dp_T^W$

Based on Eq. (2), we use the calculated  $R_{pT}$  in Ref. [8], together with the measured  $d\sigma^Z/dp_T^Z$ , to predict the  $W$  boson transverse momentum spectrum, and compare it with our previously measured  $d\sigma^W/dp_T^W$  [1]. This is shown in Fig. 2, and is an update of the result given in Ref. [8] using our final data samples. For simplicity, we use the measured  $p_T^Z$  distribution from Table 1. A better prediction for  $p_T^W$  can be obtained from the combination of our published  $p_T^Z$  [2] and the corresponding measurement from CDF [9]. Fig. 2 shows the measured differential cross section plotted at the center of the bin.

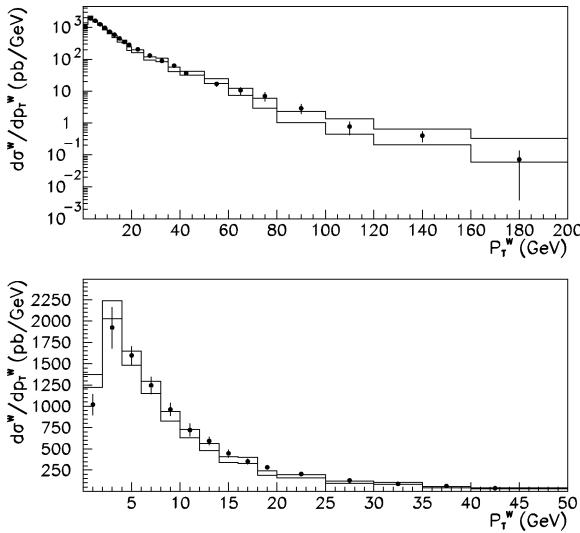


Fig. 2. Differential cross section for  $W$  boson production as a function of  $pt^W$  shown for the entire  $pt^W$  range (upper plot) and the low  $pt^W$  region (lower plot). The points are the DØ data; the error bars do not include the 4.3% error in the luminosity. The histograms represent the upper and lower 68% confidence level limits of the prediction [8] obtained from the ratio method.

The upper and lower 68% confidence level limits for the prediction are plotted as histograms. The extracted transverse momentum distribution agrees well with the measurement: the Kolmogorov–Smirnov probability [15]  $\kappa$  is equal to 0.987.

## 6. Conclusions

We have measured the ratio of scaled differential cross sections  $R_{pt}$  for  $W$  and  $Z$  boson production, and compared it to a purely pQCD prediction. We observe good agreement between data and theory over the entire  $pt$  spectrum. For completeness, we have used the theoretical prediction for  $R_{pt}$ , together with our measurement of the differential  $Z$  boson production cross section, to extract the differential cross section for  $W$  production. As expected, this prediction agrees with our published result. From this first study of the method of Ref. [8] for predicting  $W$  boson properties, we conclude that, once the high statistics samples of  $Z$  boson events expected from Run 2 at the Tevatron become available, this new approach should lead to smaller overall uncertainties on the measured mass

and width of the  $W$  boson, compared to current methods used at hadron colliders.

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